

## MASSIVE BLACK HOLES IN CENTRAL CLUSTER GALAXIES

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## ABSTRACT

We explore how the co-evolution of massive black holes (MBHs) and galaxies is affected by environmental effects, addressing in particular MBHs hosted in the central galaxies of clusters (we will refer to these galaxies in general as ‘CGs’). Recently the sample of MBHs in CGs with dynamically measured masses has increased, and it has been suggested that these MBH masses ( $M_{\text{BH}}$ ) deviate from the expected correlations with velocity dispersion ( $\sigma$ ) and mass of the bulge ( $M_{\text{bulge}}$ ) of the host galaxy: MBHs in CGs appear to be ‘over-massive’. This discrepancy is more pronounced when considering the  $M_{\text{BH}} - \sigma$  relation than the  $M_{\text{BH}} - M_{\text{bulge}}$  one. We show that this behavior stems from a combination of two natural factors, (i) that CGs experience more mergers involving spheroidal galaxies and their MBHs, and (ii) that such mergers are preferentially gas-poor. We use a combination of analytical and semi-analytical models to investigate the MBH-galaxy co-evolution in different environments and find that the combination of these two factors explains the trends observed in current data-sets.

*Subject headings:* galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation — black hole physics

## 1. INTRODUCTION

The discovery of correlations between MBHs and their hosts (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000) has been taken as one of the main elements in support of a co-evolution between MBHs and galaxies, that in turn brought to the suggestion that energy input from an accreting MBHs, as quasar or Active Galactic Nucleus (AGN) may regulate star formation in the host, or create a symbiosis between MBH and stellar growth. Indeed, theoretically there is reason to expect that energy or momentum driven outflows establish correlations that scale as  $M_{\text{BH}} \propto \sigma^5$  and  $M_{\text{BH}} \propto \sigma^4$  respectively (Silk & Rees 1998; Fabian 1999). The correlations between MBHs and galaxies, derived on a sample of about 50-70 MBHs (e.g., Gültekin et al. 2009; Graham et al. 2011; McConnell & Ma 2012) are also extrapolated to the whole population, assuming that each galaxy hosts a MBH consistent with the correlation and its scatter to derive global properties, such as the mass density in MBHs today (e.g., Shankar et al. 2004). These correlations, or deviations from such correlations, also appear to hold the key to understanding the formation and evolution of the MBH population (Volonteri 2012, and references therein).

Recent measurements of the masses of MBHs in CGs (we include in this definition central dominant galaxies as well as brightest cluster galaxies) seem to suggest that these MBHs are ‘over-massive’ compared to expectations from of the  $M_{\text{BH}} - \sigma$  relation, but they appear more consistent, albeit with a large scatter, with the  $M_{\text{BH}} - L_V$  relation (McConnell et al. 2011, 2012). McConnell & Ma (2012) and Graham & Scott (2012) fit for the  $M_{\text{BH}} - \sigma$  correlation find that the relation becomes much steeper,

e.g. from  $M_{\text{BH}} \propto \sigma^{4.2}$  (Gültekin et al. 2009) to  $M_{\text{BH}} \propto \sigma^{5.6}$ . The same does not happen for the  $M_{\text{BH}} - M_{\text{bulge}}$  relation, that appears to be consistent with being linear in both cases (although including MBHs in CGs increases the normalization). There is also tentative evidence for over-massive MBHs in CGs from comparisons with the expectations from the Fundamental Plane of black hole activity (Hlavacek-Larrondo et al. 2012). Feedback affecting galaxies in different ways depending on potential well (Booth & Schaye 2011) and environment, via gas-rich mergers and cooling flows (Zubovas & King 2012) has been proposed to be partially responsible for the properties of these MBHs.

We investigate here two guiding ideas related to the influence of mergers between spheroidal, gas-poor galaxies (‘dry’ mergers) and of MBH-MBH mergers to determine the astrophysical drivers of the possibly different relationship between MBHs and their hosts in the case of CGs. It is well established from the theoretical point of view that (parabolic) dry mergers consistently grow a galaxy’s mass, luminosity and radius more than a galaxy’s velocity dispersion (e.g., Ciotti & van Albada 2001; Ciotti et al. 2007; Naab et al. 2009; Nipoti et al. 2009; Shankar et al. 2011; Oser et al. 2012; Hilz et al. 2012), especially when a galaxy is dominant over the general population (Ciotti et al. 2007; Naab et al. 2009). Qualitatively this implies that eventually the largest galaxies deviate from the  $M_{\text{BH}} - \sigma$  relation. Therefore, if CGs grew predominantly through dry mergers (e.g., Ostriker & Tremaine 1975; Hausman & Ostriker 1978), and their MBHs grew mostly through MBH-MBH mergers (Malbon et al. 2007; Yoo et al. 2007) in such dry mergers then the expectation is that they will be outliers in the  $M_{\text{BH}} - \sigma$  relation (see also Boylan-Kolchin et al. 2006; Lauer et al. 2007; Zhang et al. 2012). Support for the influence of dry mergers in shaping the structural properties of CGs comes from their steeper radius–luminosity relation and flatter Faber-Jackson relation (e.g., Lauer et al. 2007; Bernardi et al. 2007;

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Desroches et al. 2007). Additionally, if MBHs in CGs experience a significant mass increase because of MBH-MBH mergers with respect to MBHs in a field environment, the extra boost in mass may also contribute to explain the properties of MBHs in CGs, if gas accretion is responsible for establishing the relationships in the first place.

We present here models of MBH growth in galaxies that take into account both the cosmic environment, i.e., the frequency and properties of galaxy and MBH mergers, as well as the evolution of the virial properties of galaxies during galaxy mergers, with particular attention to mergers between gas-poor spheroids.

## 2. MERGERS AND BLACK HOLE GROWTH

We use the latest incarnation of our semi-analytical models (Volonteri et al. 2012) to provide a simple estimate of the influence of dry mergers on the build-up of MBHs and their hosts in different environments. We summarize here the main assumptions. We keep our model for galaxy morphology and gas content as simple as possible. Morphology is related to the merger history, using a three-parameter model, where spheroid (we equivalently refer to spheroids and ‘gas-poor’ galaxies in the following) formation depends on both halo mass ratio and the absolute halo mass, and a spheroid can re-acquire a disc through cold flows and mergers with gas-rich galaxies. Koda et al. (2009) show that the fraction of disc- vs spheroid-dominated galaxies is well explained if the only merger events that lead to spheroid formation have mass ratio  $>0.3$  and virial velocity  $> 55 \text{ km s}^{-1}$ ; also, the merger timescale (calculated following Boylan-Kolchin et al. 2008) must be less than the time between when the merger starts and today,  $z = 0$ . We assume that spheroids form after a merger that meets these requirement. We additionally allow gas to re-condense (‘gas-rich’ galaxy) after 5 Gyrs in galaxies with virial velocity  $< 300 \text{ km s}^{-1}$  where no major mergers occurred to include the effect of gas accretion and cold flows.

We wish to keep our models as simple as possible, while making sure that the properties of the MBHs we study are correctly determined through the cosmic evolution of their hosts. We do not explicitly model the evolution of the baryonic component of the host galaxies through cooling, star formation and various feedbacks (see Fanidakis et al. 2011; Fontanot et al. 2011; Hirschmann et al. 2012, and references therein for models that treat in detail semi-analytically the baryonic component of galaxies and its link to MBH evolution). In our models we use only one parameter to link the host halo to the central MBH, and it is the halo’s velocity dispersion. We link the velocity dispersion of the halo to the asymptotic virial velocity ( $v_{\text{vir}}$ ) assuming a spherical, isothermal halo, so that  $\sigma_{\text{vir}} = v_{\text{vir}}/\sqrt{2}$ . We calculate the circular velocity from the mass of the host halo and its redshift.

At high redshift we seed dark matter halos with MBHs created by gas collapse. Specifically, we adopt here the formation model detailed in Natarajan & Volonteri (2011) based on Toomre instabilities (Lodato & Natarajan 2006).

Our model includes MBH-MBH mergers, merger-

Table 1

$M_{\text{halo}}$ ( $M_{\odot}$ )	Dry mergers with MBHs	Dry mergers (total)	$M_{\text{BH},0}/M_{\text{acc}}$
$10^{15}$	4.2 ( $\sigma_n=2.0$ )	4.6 ( $\sigma_n=2.1$ )	$10.9 \pm 9.7$
$10^{14}$	1.7 ( $\sigma_n=1.3$ )	1.8 ( $\sigma_n=1.4$ )	$2.4 \pm 1.0$
$4 \times 10^{13}$	0.3 ( $\sigma_n=0.5$ )	0.4 ( $\sigma_n=0.6$ )	$1.9 \pm 0.7$
$2 \times 10^{13}$	0.2 ( $\sigma_n=0.4$ )	0.3 ( $\sigma_n=0.5$ )	$2.0 \pm 0.7$
$10^{13}$	0.1 ( $\sigma_n=0.2$ )	0.1 ( $\sigma_n=0.2$ )	$1.8 \pm 1.8$

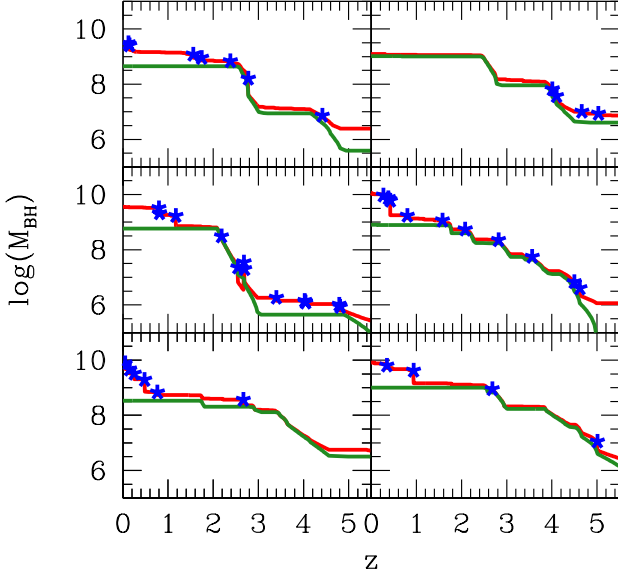
**Note.** — Number of dry mergers (including their  $1-\sigma$  variance) experienced by the central galaxy, regardless of its morphology, of a halo that by  $z = 0$  has the mass listed in Column 1, and growth channels for its MBH.

driven gas accretion, stochastic fueling of MBHs through molecular cloud capture, and a basic implementation of accretion of recycled gas. Details are given in Volonteri et al. (2012). Despite its simplicity, our approach produces a population of MBHs and AGN consistent with the observed one in terms of, e.g., luminosity function of AGN, relationship between MBHs and their hosts, high-redshift quasars.

In Table 1 we list the number of dry mergers experienced over its lifetime by the central galaxy of a halo, as a function of the halo mass at  $z = 0$  (the average is performed over 20 to 35 different halos for each halo mass). We can consider the  $10^{15} M_{\odot}$  halo as a cluster-sized halo, the  $10^{14} M_{\odot}$  halo as a group-sized halo, and the smaller halos as galaxy-sized ones. The dry-ness of a galaxy during a merger is determined in a very simple way, i.e. we require that both merging galaxies are gas-poor.

As expected, the number of dry mergers decreases as the halo mass decreases, therefore their influence will be strongest for central galaxies in clusters, and possibly in groups. In Fig. 1 we focus on the MBH growth in six different realizations of  $10^{15} M_{\odot}$  halos. For instance, the growth of the two MBHs in the top panels is strikingly different. In one case it is dominated by MBH-MBH mergers at  $z < 2$ , while the second MBH does not experience any important MBH-MBH merger at late cosmic time. If we define the relative growth through mergers as the difference between the MBH mass at  $z = 0$ ,  $M_{\text{BH},0}$ , and the cumulative accreted mass,  $M_{\text{acc}}$ , we can estimate the importance of MBH-MBH mergers in a MBH’s history. In Table 1 we report this information in the fourth column. The definition we adopt cannot account for accretion on the MBHs that merge with the one in the central galaxy. Therefore, the fact that we find  $M_{\text{BH},0}/M_{\text{acc}} > 1$  does *not* mean that MBHs grow predominantly through mergers, and in fact if we removed accretion from our models the final MBH mass would be about two orders of magnitude smaller. Overall, therefore, MBHs grow through accretion of gas, in a way consistent with independent estimates (Yu & Tremaine 2002).

To test the robustness of our results we changed the MBH feeding scheme, by assuming that all MBH accretion activity is driven by galaxy mergers, that the accretion rate is fixed to 30% of the Eddington rate and that accretion stops once the MBHs have reached the value of  $M_{\text{BH}} = 10^8 (\sigma_{\text{vir}}/200 \text{ km s}^{-1})^4 M_{\odot}$ . We find that while



**Figure 1.** Examples of MBH growth in six randomly chosen central galaxies of  $10^{15} M_{\odot}$  halos. The red solid curve shows the MBH mass at a given time, the dark green dashed curve shows the cumulative mass gained in accretion events, blue asterisks mark MBH-MBH mergers with mass ratio  $> 1 : 10$ . As an example, the growth of the MBH in the top-left panel is dominated by MBH-MBH mergers, while that of the MBH in the top-right panel is dominated by accretion through various channels (merger driven in gas-rich mergers, through accretion of gas clouds, and through recycled gas).

small quantitative differences exist, qualitatively the results of our investigation are unchanged. We conclude that, if the  $M_{BH} - \sigma$  relation is established because of accretion-driven feedback (e.g., Silk & Rees 1998; Fabian 1999), MBHs in CGs may not necessarily obey the same the  $M_{BH} - \sigma$  relation, as their masses may grow substantially through mergers after accretion dwindles.

### 3. MERGERS AND GALAXY STRUCTURE

From the evolutionary histories of our models we extract the series of mergers that the central galaxy of the main halo experiences from  $z = 1$ . We record the MBH mass in the merging galaxies and the dark matter halo masses,  $M_{h,1}$  and  $M_{h,2}$ , (here onwards the subscripts refer to each one of the two galaxies, with the convention that subscript 1 labels the central galaxy of the main halo, which is not necessarily the most massive galaxy of the merging pair). To each halo at the starting redshift we assign a stellar mass,  $M_*$ , using the fits by Behroozi et al. (2010, see also Nipoti et al. 2012), a projected velocity dispersion,  $\sigma$ , consistent with the Faber-Jackson relation, and an effective radius determined through the Fundamental Plane (Binney & Tremaine 2008, pages 23-24), including scatter in all relations. We included a redshift dependence of the Faber-Jackson and Kormendy relations, using the scalings suggested by Oser et al. (2012), namely that  $\sigma \propto (1+z)^{0.44}$  and  $R_e \propto (1+z)^{-1.44}$  (see also Nipoti et al. 2012). We then calculate the  $M_*$  and  $\sigma$  resulting from the merger following Ciotti et al. (2007) as follows. We account for weak homology by relating  $\sigma$

to the virial velocity dispersion,  $\sigma_v$ , as:

$$\frac{\sigma}{\sigma_v} \simeq \frac{24.31 + 1.91n + n^2}{44.23 + 0.025n + 0.99n^2}; \quad (1)$$

$$\frac{r_v}{R_e} \simeq \frac{250.26 + 7.15n}{77.73 + n^2}, \quad (2)$$

adequate for Sersic index  $n$ ,  $2 \lesssim n \lesssim 12$ . We assume that the Sersic index of the resulting galaxy is  $n = 1 + \max(n_1, n_2)$ , where  $n_1$  and  $n_2$  are the Sersic indices of the progenitors (each galaxy starts with  $n$  determined from the virial coefficient,  $K_v(n) = GM_*/R_e\sigma^2 = (r_v/R_e) \times (\sigma_v/\sigma)^2$ ).

In case of mergers between gas-rich galaxies or between a gas-poor and a gas-rich galaxy, we assume that each gas-rich galaxy has a gas mass  $M_g = \alpha M_*$ , with  $\alpha = 4$  and that a fraction  $\eta = 0.05$  ( $M_{h2}/M_{h1}$ ) of the gas is converted into stars:

$$M_* = M_{*1} + M_{*2} + \eta(M_{g1} + M_{g2}). \quad (3)$$

We find the velocity dispersion of the newly formed galaxy<sup>4</sup> as:

$$\sigma_v^2 = \frac{M_{\text{tot}1}}{M_{\text{tot}}} A_1 \sigma_{v1}^2 + \frac{M_{\text{tot}2}}{M_{\text{tot}}} A_2 \sigma_{v2}^2, \quad (4)$$

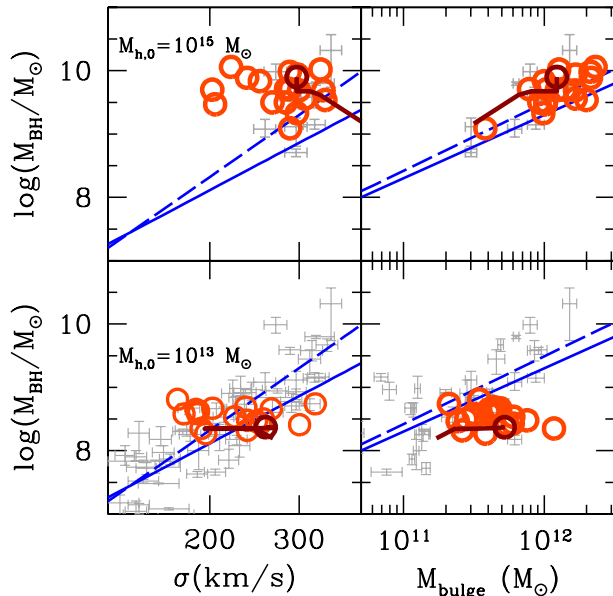
where  $M_{\text{tot}1} = M_{*1} + M_{g1}$ ,  $M_{\text{tot}2} = M_{*2} + M_{g2}$ ,  $M_{\text{tot}} = M_{\text{tot}1} + M_{\text{tot}2}$ , and

$$A_1 = 1 + \frac{\eta\alpha_1}{1 + \alpha_1}, \quad (5)$$

and a similar expression holds for  $A_2$ . From the second merger of the sequence onwards, the central galaxy retains the properties derived in the previous step, while we assign  $M_{*2}$  and  $\sigma_{v2}$  to the merging galaxy as described above. Throughout our experiment, the MBH mass is determined from the semi-analytical model, that includes both accretion and MBH-MBH mergers. We note that not all galaxies host MBHs, i.e., the merging galaxy may or may not contribute to the MBH growth.

We present the results of this experiment in Fig. 2. In the top two panels we focus on MBHs hosted in the central galaxy of  $10^{15} M_{\odot}$  halos at  $z = 0$  (akin to CGs), while in the bottom panel the focus is the central galaxy of a galaxy-sized halo ( $10^{13} M_{\odot}$  at  $z = 0$ ). We assessed that the results at  $z = 0$  are qualitatively unchanged if we ignore the redshift evolution in the Faber-Jackson and Kormendy relations, with MBHs and galaxies occupying the same region in the  $M_{BH} - \sigma$  relation. CGs are characterized by MBHs that consistently deviate from the expected correlations, being over-massive at fixed galaxy properties, occupying the same range as observations. MBHs in elliptical galaxies that are not CGs, where the influence of MBH-MBH mergers and dry mergers is much milder tend instead to sit closer to the global MBH-host correlations. This result can be interpreted as overall steeper and higher normalized relations with respect to previous estimates (compare solid and dashed black lines in Fig. 2). At  $z < 1$  most CGs are the dominant galaxies,

<sup>4</sup> The presence of dark matter can be included through an extra  $\alpha_{DM}$  parameter in our scheme (see Ciotti et al. 2007), assuming that stars and dark matter are similarly distributed. Inclusion of the dark matter halo represents a small correction as long as we are interested in the region within the effective radius.



**Figure 2.** Examples of  $M_{BH} - \sigma$  and  $M_{BH} - M_{bulge}$  in 20 randomly chosen central galaxies of  $10^{15} M_{\odot}$  (top) and  $10^{13} M_{\odot}$  (bottom) halos. The gray errorbars are observed MBHs and galaxies (McConnell & Ma 2012, in the top panel we show CGs only), the solid blue lines are the fits derived by Gültekin et al. (2009) and Marconi & Hunt (2003), the dashed lines are the fits from McConnell & Ma (2012). The red dots show the location of model MBHs at  $z = 0$ . The dark red curves show two examples from the evolutionary histories: horizontal rightward swings in the  $M_{BH} - \sigma$  panels occur when the galaxy merges with a more massive galaxy, vertical (leftward) movement is characteristic of dry mergers with similar (smaller) galaxies.

and they merge with smaller galaxies that consistently have  $\sigma_{v2} < \sigma_{v1}$  and therefore their velocity dispersion cannot increase (see Eq. 4). On the other hand a non-CG galaxy has a higher chance of merging with a galaxy with  $\sigma_{v2} > \sigma_{v1}$ , with the merger remnant having  $\sigma_v > \sigma_{v1}$  (see the dark red tracks in Fig. 2 for an example).

We note (see also Nipoti et al. 2012) that this scheme tends to overproduce stellar masses by  $z = 0$ . In fact the  $M_{star} - M_h$  relationship peaks at  $M_h = 10^{12} M_{\odot}$ , therefore by merging galaxies close to the peak the remnant galaxy ends up having an increased  $M_{star} - M_h$ . While our merger sequence includes both galaxies below, at and above the peak, we find that we consistently overpredict stellar masses at  $z = 0$  with respect to the scaling we would obtain directly from the  $M_{star} - M_h$  relationship, and that in general bulges appear too massive (this is evident in the right panels of Fig. 2). This problem would be alleviated if we included corrections for mass lost in the merging process (Nipoti et al. 2003). We also consider parabolic mergers only, where energy is perfectly conserved. However, not all mergers involving a CG are necessarily parabolic. On the one hand, since the galaxies move in the potential of the cluster, hyperbolic mergers may occur. On the other hand, Nipoti et al. (2003) note the effect of dynamical friction, that braking the galaxy’s orbit may induce elliptical merging. Hyperbolic and elliptical mergers have competitive effects on the evolution of  $\sigma$ . Elliptical mergers with negative orbital energy increase the final  $\sigma$ , and viceversa. This effect, as well as

the suggestion by Hilz et al. (2012) that energy transfer from bulge to halo grows the velocity dispersion, would improve the match of our exercise with observations.

#### 4. CONCLUSIONS

In this Letter we have highlighted the effects that mergers have on the MBH population in CGs. Two main factors contribute to their evolution. Firstly, CGs experience many more dry mergers with spheroids. Parabolic dry mergers grow a galaxy’s mass, luminosity and radius more than a galaxy velocity dispersion (e.g., Ciotti et al. 2007; Nipoti et al. 2009; Shankar et al. 2011; Oser et al. 2012; Hilz et al. 2012). If in a given merger  $M_{BH}$  and  $M_{bulge}$  increase relatively more than  $\sigma$  (see the discussion in Ciotti et al. 2007), a sequence of such mergers will lead to more massive MBHs at fixed  $\sigma$ . In Fig. 2 (left panels) this corresponds to moving upward faster than rightward.

Secondly, the sheer number and mass contribution of MBH-MBH mergers occurring in CGs galaxies is much higher (see Table 1). If we assume that correlations between MBHs and hosts are established because of AGN feedback (e.g., Silk & Rees 1998; Fabian 1999; Di Matteo et al. 2005; Hopkins et al. 2009), then if MBH mergers contribute to the MBH growth *after* the bulk of quasar/AGN activity has ceased (Fig. 1), the MBH mass increase brought by these mergers will push the MBH upwards and out from the correlation established through feedback. One important caveat, however, is whether MBH binaries can merge efficiently in gas-poor environments, because of the so-called ‘final parsec problem’ (e.g., Begelman et al. 1980), although various effects, such as triaxiality and rotation, as well as the presence of massive perturbers, may increase the orbital decay rate, see Colpi & Dotti (2011) for a recent review.

Our models are at variance with other models that study the impact of MBH mergers on the establishment of correlations (e.g., Jahnke & Macciò 2011) as we do not assume that MBHs populate all galaxies. In fact, the presence or absence of a central MBH leads to different evolutionary paths in the  $M_{BH} - \sigma$  and  $M_{BH} - M_{bulge}$  relations. We can consider two extreme cases. Let us assume that all galaxies host a MBH. Then at each merger  $M_*$  and  $M_{BH}$  increase as the sum of those in the two galaxies, barring for the effects of stellar escapers (Nipoti et al. 2003; Hilz et al. 2012) and non-linear addition of MBH masses (Ciotti & van Albada 2001; Ciotti et al. 2007). However, Eq. 3 shows that  $\sigma$  would stay the same or slightly decrease. This corresponds to a vertical upward movement in the  $M_{BH} - \sigma$  plot, eventually leading to MBHs that are over-massive for their  $\sigma$ , but are not outliers in the  $M_{BH} - M_{bulge}$  correlation. The other extreme case assumes that only the main galaxy hosts a MBH. Then at each merger  $M_*$  increases, while  $M_{BH}$  and  $\sigma$  do not. Eventually the MBH in the galaxy that results from the merger sequence will be under-massive for its bulge mass, but it will not be an outlier in the  $M_{BH} - \sigma$  relation.

Broadly speaking, the models of MBH evolution that we adopt for this Letter (Volonteri et al. 2012) predict that the most massive MBHs, except for those hosted in CGs, are those that are best correlated with their hosts (Volonteri & Natarajan 2009) if their build-up is driven by a combination of accretion and mergers that

includes both gas-rich and gas-poor galaxies, and dispersion should increase at low MBH/galaxy masses (see Fig. 2, top panel in Volonteri et al. 2012), where the MBH mass, even at  $z = 0$  traces the properties of the MBH formation mechanism (van Wassenhove et al. 2010). It may well be that if different processes shape the MBH mass at different galaxy masses (MBH formation at the lowest masses, AGN feedback at intermediate masses, MBH and dry mergers at the highest masses), there is not a unique link that straddles throughout the whole range.

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